Temperature measurements from relative populations of excited states with INDRA

M. Assenard, C. Lebrun, Pascal Lautridou, F. Gulminelli, Philippe Eudes, Marie Germain, D. Gourio, J.L. Laville, Vincent Métivier, A. Rahmani, et al.

ECOLE DES MINES DE NANTES

SUBATECH

UMR Université, Ecole des Mines, IN2P3/CNRS

LABORATOIRE DE PHYSIQUE SUBATOMIQUE
ET DES TECHNOLOGIES ASSOCIEES

TEMPERATURE MEASUREMENTS FROM RELATIVE POPULATIONS OF EXCITED STATES WITH INDRA

*M. Assenard, C. Lebrun, P. Lautridou, F. Gulminelli,
Ph. Eudes, M. Germain, D. Gourio, J.L. Laville,
V. Métivier, A. Rahmani, T. Reposeur
and the INDRA Collaboration*

Rapport Interne SUBATECH 97-15
LPPC 97-11
IPNO-DRE 97-21
DAPNIA/SPhN 97-33
GANIL P 97-25
LYCEN 97-

4, RUE ALFRED KASTLER. BP 20722. 44307 NANTES CEDEX 03. TELEPHONE 02 51 85 81 00. TELECOPIE 02 51 85 84 79. E-mail : @ FRCPN11.IN2P3.FR

Temperature Measurements from relative populations of excited states with INDRA

M. Assenard[a], C. Lebrun[a] , P. Lautridou[a] , F. Gulminelli[e] , Ph. Eudes[a], M. Germain[a], D. Gourio[a], J.L. Laville[a], V. Métivier[a],A. Rahmani[a], T. Reposeur[a], G. Auger[d], Ch.O. Bacri[c], J. Benlliure[d], E. Bisquer[f], F. Bocage[e], B. Borderie[c], R. Bougault[e], R. Brou[e], Ph. Buchet[b] J.L. Charvet[b], A. Chbihi[d], J. Colin[e], D. Cussol[e], R. Dayras[b], E. De Filippo[b], A. Demeyer[f], D. Dore[c], D. Durand[e], J.D. Frankland[c], E. Galichet[f], E. Genouin-Duhamel[e], E. Gerlic[f], D. Guinet[f], Ph. Lautesse[f], J.F. Lecolley[e], A. Le Févre[d], T. Lefort[e], R. Legrain[b], O. Lopez[e], M. Louvel[e], N. Marie[d], L. Nalpas[b], A.D. Nguyen[e], M. Parlog[g], J. Péter[e], E. Plagnol[c], M.F. Rivet[c], E. Rosato[h], R. Roy[i], F. Saint-Laurent[d], S. Salou[d], M. Squalli[c], J.C. Steckmeyer[e], M. Stern[f], B. Tamain[e], O. Tirel[d], L. Tassan-got[c], E. Vient[e], C. Volant[b], J.P. Wieleczko[d].

[a] *SUBATECH, IN2P3-CNRS, EMN et Université, 44072 Nantes Cedex 03, France.*
[b] *CEA, DAPNIA/SPhN, CEN Saclay, 91191 Gif sur Yvette Cedex, France.*
[c] *Institut de Physique Nucléaire, IN2P3-CNRS, 91406 Orsay Cedex, France.*
[d] *GANIL, CEA, IN2P3-CNRS, B.P. 5027, 14021 Caen Cedex, France.*
[e] *LPC, IN2P3-CNRS, ISMRA et Université, 14050 Caen Cedex, France.*
[f] *IPN Lyon, IN2P3-CNRS et Universié, 69622 Villeurbanne Cedex, France.*
[g] *Intitute of Physics and Nuclear Engineering, IFA, P.O. Box MG6, Bucharest, Romania.*
[h] *Dipartimento di Scienze, Univ. di Napoli, 80125 Napoli, Italy.*
[i] *Laboratoire de Physique Nucléaire, Département de Physique, Université Laval, Québec G1K7P4, Canada.*

Abstract

The 4π array INDRA allows to detect and identify nearly all final products of a collision. Therefore, using global variable analysis, it is possible to select well-defined sources and to measure their excitation energies. For the first time, INDRA has been used to analyse resonances observed in correlation functions, giving thus the possibility to probe the caloric curve (correlation between the excitation energy and the temperature). First results obtained for the reaction

${}^{36}_{18}Ar+{}^{58}_{28}Ni$ at 95 MeV/nucleon are presented where the projectile-like apparent temperature has been evaluated. Moreover, the measured populations of excited states are compared with the predictions of a statistical model which includes an original hypothesis of excluded volume for species at the freeze-out.

Introduction

In intermediate energy heavy-ion reactions, very hot nuclei can be produced. The study of their statistical decay allows to investigate the equation of state of nuclear matter and the possible occurence of a phase transition. In this context, the thermodynamical temperature appears as an important parameter. Several experimental ways have been used to evaluate it : slope of particle energy spectra, double isotopic ratios and relative populations of excited states [1]. These three thermometers are rarely used simultaneously owing to experimental constraints but the INDRA multidetector offers this unique opportunity to obtain results from the three methods in the same experimental conditions. In a previous paper [2] data from the first and the second method have already been compared with a simple model of thermodynamical equilibrium, in the Ar + Ni collisions.

In this contribution we report on measurements of excited states populations for the system Ar + Ni at 95 MeV per nucleon. In the first section, the population extraction is briefly described, then the advantages and drawbacks of INDRA for this type of measurement are examined. In the third section details about the experimental analysis with INDRA are presented. Data are finally compared with a quantum statistical model (QSM) to test a simple assumption of "excluded volume" at the freeze-out and to extract the initial thermodynamical temperature.

1 Experimental method to measure populations of excited levels

To identify two particles coming from unstable fragments among all the pairs emitted in a collision, it is necessary to measure a kinematic variable connected with the excitation energy of the fragment. The most commonly used is the relative momentum defined as : $q = \left|\mu\left(\frac{\overrightarrow{P_1}}{M_1} - \frac{\overrightarrow{P_2}}{M_2}\right)\right|$ where μ is the reduced mass, $\overrightarrow{P_i}$ and M_i are the momentum and the mass of the two concerned particles respectively. The distribution of this variable for pairs emitted by excited fragments shows for each level a peak more or less separated from the next one depending on its width, its intensity and the energy difference. These pairs are mixed with other coincident particles which are deflected in the Coulomb field giving an anticorrelation behaviour to this component. Enhancement of the correlation and anticorrelation effects which are superimposed to the uncorrelated pairs, is usually obtained by displaying the correlation function [3] :

$$1 + R(q) = N\frac{\sum Y_{12}(P_1, P_2)}{\sum Y_1(P_1).Y_2(P_2)} = N\frac{Num(q)}{Den(q)}, \tag{1}$$

where N is a normalization factor, $Y_{12}(P_1, P_2)$ is the coincidence yield of particles 1 and 2 at momenta P_1 and P_2, respectively; $Y_i(P_i)$ is the single particle yield for the ith particle of momentum P_i obtained from particles detected in two different events (see Fig. 1). Assuming a Coulomb anti-correlation shape it is possible to deduce by subtraction the resonance yield. The last step is to estimate the efficiency of the detector for the involved pairs because some of them are not detected and others fall in the same cell.

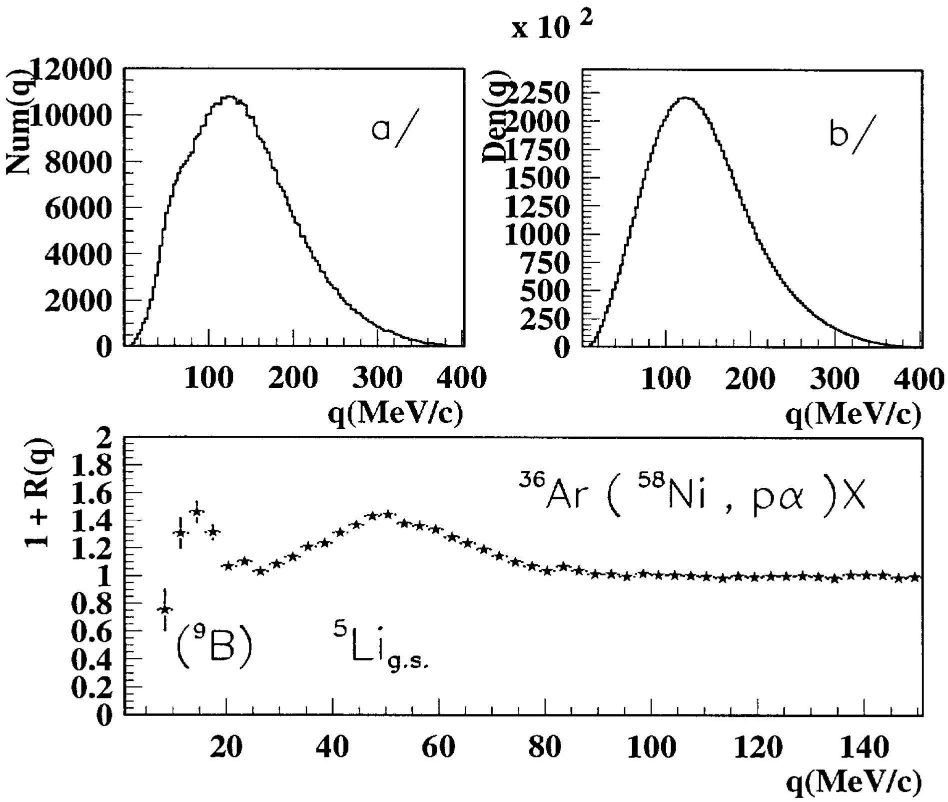

Figure 1: *Pattern of experimental correlation function. The 1.a and 1.b distributions represent the numerator and the denominator of formula 1, respectively. The ^9B peak is interpreted as 2α + p decay.*

2 The INDRA detector as a calorimeter and as a correlator

Event selection :

The INDRA detector [4] has been built to detect nearly all charged products in heavy ion collisions. It is then possible to reconstruct event by event the spatial distribution of the products and to deduce from the momenta of fragments with $A > 2$ an estimation of the velocity vector of each involved emission source [2]. For the studied reaction Ar + Ni at 95 MeV per nucleon it has been observed that the binary dissipative collisions are dominant. Data used in the following will involve only those events where fragments and particles are emitted by projectile-like (PL) or target-like (TL) fragments. Particle kinetic energy spectra in the center of mass of the PL or the TL are sufficiently isotropic to confirm that preequilibrium effects are weak. It is then possible to deduce the excitation energy from the calorimetry formula :

$$E_S^* = \sum_i (\Delta m_i + E_{Ki}) - \Delta m_S, \qquad (2)$$

Δm_i being the mass excess of particle i, Δm_S that of the source, and E_{Ki} the ith particle kinetic energy in its source frame. In the summation the kinetic energy of neutrons was taken as the average kinetic energy of protons in the same conditions, minus 2 MeV to take into account the absence of Coulomb barrier. High excitation energies can be reached and the whole system can vaporize. This situation is experimentally defined by the absence of fragments with $Z > 2$ [5].

In the following we will present data from vaporization events for which PL and TL emissions were distinguished. The excitation energy distributions are then centered at 17.7±3.9 MeV (PL), and at 14.6±3.0 MeV (TL) (errors are the standard deviations)[6,7]. As the PL emission products are completely detected, we will select only this emission source in order to study the correlation between the temperature and the excitation energy. The statistics is then sufficient to share the data in three excitation energy bins (Fig. 2).

INDRA as a 4π correlator :

The granularity of the INDRA detector was not initially defined according to resonances study constraints [4], but it appeared that the forward part of INDRA may reasonably be used for measuring correlation functions. However the observed widths of the resonance peaks are always dominated by acceptance effects : for example in the case of the $^6Li^*_{2.18MeV}$ excited state the natural Γ width ($\Gamma = 0.024$ MeV) is enlarged to $\Gamma = 0.16$ MeV .

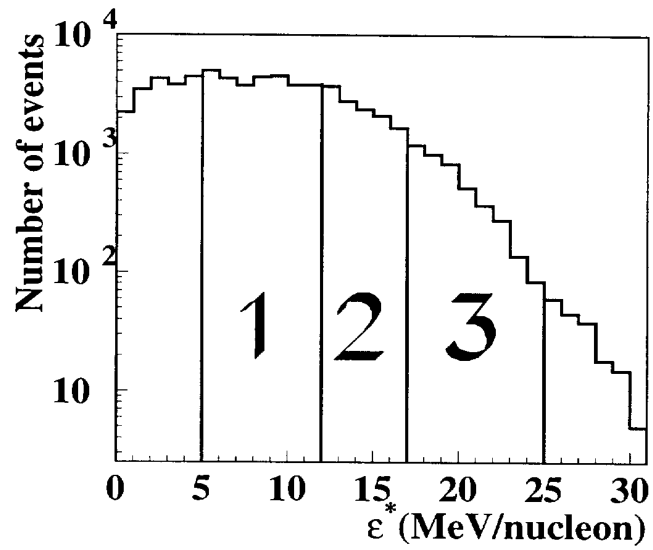

Figure 2: *Excitation energy distribution for the projectile-like in Ar+Ni binary events .*

Concerning the total statistics for the studied system, it was fitted to accumulate sufficient number of events corresponding to more central collisions. The number of resonant pairs at low relative momenta that can be extracted represents a very weak percentage of the total counting. In addition, to analyse the influence of the excitation energy, the events have to be sorted in several intervals, accordingly lowering the statistics for each bin.

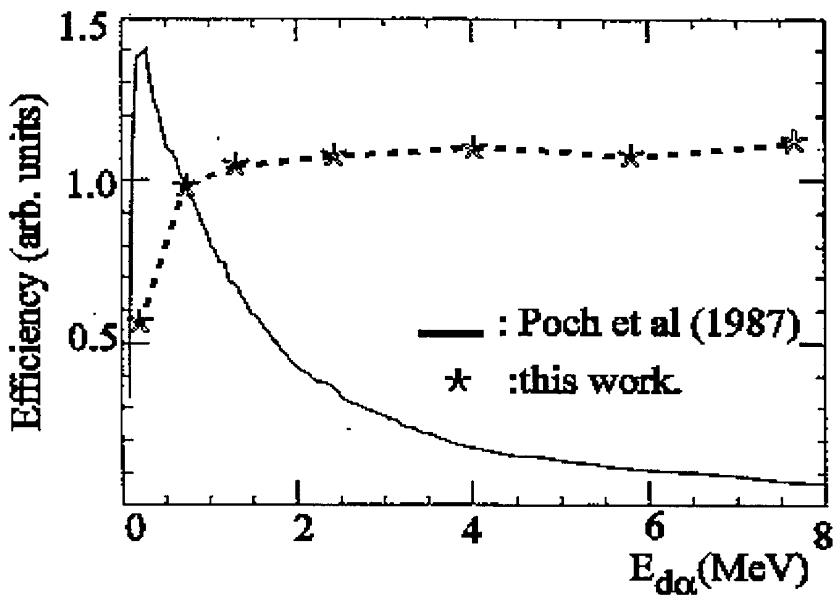

Figure 3: *Efficiency of INDRA compared with results obtained by Pochodzalla et al [8].*

However some resonances can been measured thanks to the high multiplicity of light particles in the more central collisions and to the excellent solid angle coverage of the detector. Figure 3 compares the efficiency for detecting pairs coming from excited fragments with INDRA and with the hodoscope used by Pochodzalla et al [8].This quantity which depends on the excitation energy of excited levels remains nearly constant with INDRA at variance with the more classical hodoscopes, just reflecting the good geometrical acceptance of INDRA.

3 Coulomb background extraction and efficiency calculation

Coulomb background:

In order to reconstruct the Coulomb background it is useful to observe the shape of correlation functions for pairs which do not exhibit resonances at low relative momenta. To take into account charge and mass effects on the anticorrelation behaviour Kim et al [9] used a kinematic variable, called reduced relative velocity and defined as :

$$V_{red} = \frac{q}{\mu\sqrt{Z_1 + Z_2}},$$

where Z_i is the charge of particle i. Using this "renormalization" variable, all correlation functions look very similar. Presently we constructed correlation functions for the 4 different non-resonant couples (p,d),(d,d),(t,^3He) and (d,^6Li). Then the Coulomb correlation functions are drawn taking care of this self-consistent data analysis and the distributions of the resonant pairs are obtained after subtraction of the Coulomb background.

An example of the procedure is shown in figure 4 for the α-α correlation function. After gaussian fits of the peaks in the excitation function, the integrals give the numbers of detected pairs associated with ^{8}Be ground state and the excited states.

The efficiency calculation :

To extract populations for each level, we have to take into account the INDRA efficiency that has been derived from simulations with the following assumptions :

- the energy spectra and the angular distributions of the excited fragments have the same shapes as those observed for stable fragments,
- the decay of the parent nuclei is isotropic in its rest frame.

Moreover, a gaussian shape is taken for each resonance.

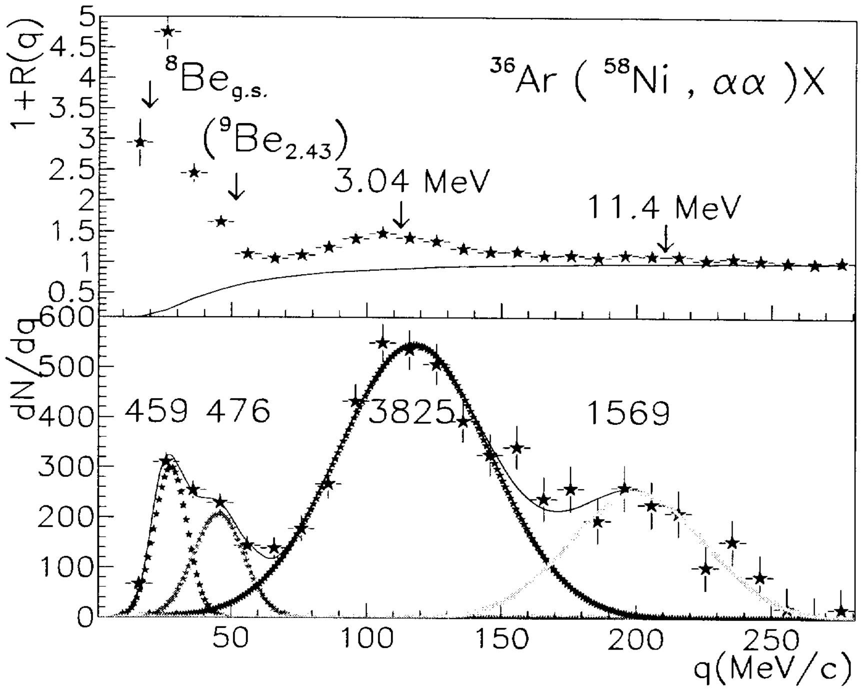

Figure 4: *Extraction of ^8Be excited states populations. The numbers of pairs are indicated for each resonance.*

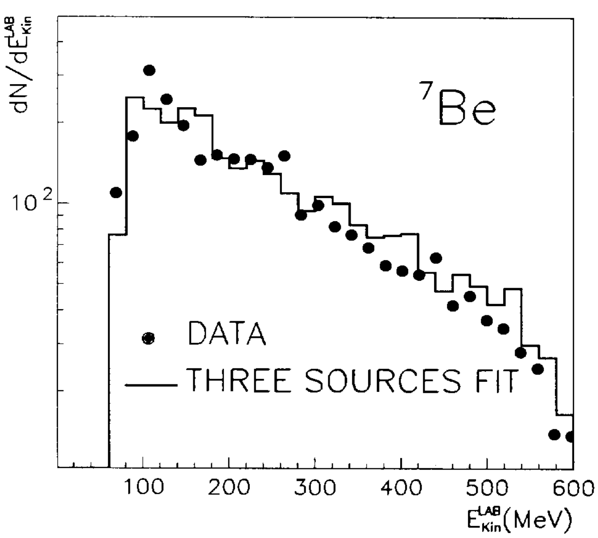

Figure 5: *Energy spectrum for* ^{7}Be *nuclei dectected in the whole solid angle of INDRA. The solid histogram corresponds to a three-sources fit.*

Each event is generated in a source rest frame according to a Maxwellian distribution:

$$\left(\frac{d^2\sigma}{d\Omega dE_i}\right)_i = N_i.(E_i - B_i).exp\left(-\frac{E_i - B}{T_i}\right) \quad (3)$$

where N_i is the weight of the ith source, E_i the energy of particle in the ith source rest frame, B_i denotes the Coulomb repulsion between the particle and the source and T_{source}, the slope parameter; the velocity of each source, V_i, is taken into account in the Lorentz transformation .The moving source fitting parameters were only used as input to the efficiency simulations, and not as true physical parameters to be discussed.
Figure 5 shows an example of the inclusive measured spectrum fitted by a moving source parametrization using three sources. After filtering, the efficiency factors are found to be around 25% and 68% for the ^8Be ground state and the 3.04 MeV excited state respectively.

4 Data analysis

Statistical model :

In the following the experimental populations of unstable nuclei will be used as a test of a theoretical scenario of the emission mechanism already applied to the description of the slope of deuteron energy spectra and of double isotopic yield ratios [2]. This quantum statistical model (QSM) [10] considers a chemically and thermally equilibrated source at temperature T and density ρ which disintegrates simultaneously. The T and ρ values are fixed in order to reproduce the experimental ratio $\frac{Z_{lcp}}{Z_{tot}}$ (where lcp means light charged particles) for a given energy. This model is valid above an excitation energy of 10 MeV per nucleon. The overall results presented below are compatible with a density of $\frac{\rho_0}{3}$ and a thermodynamical temperature increasing from 10 MeV up to 20 MeV when the excitation energy goes from 10 to 25 MeV per nucleon. In the model two assumptions are tested. The first one considers an ideal gas where the different species do not interact in the final state. As distances between particles and fragments at the freeze-out are not very large, an alternative assumption is proposed which takes into account an effective excluded volume for each species in the spirit of the Van der Waals gas. Since sequential feeding from particle decays of heavier nuclei will strongly influence the yields of excited states [11,12], feeding from discrete and continuum states is included in the model.

Experimental Results :

The first results concern vaporization events. In this case it was required that only light particles are detected (Z=1 or Z=2), and more than 90% of total charge. Each particle was associated to PL or to TL. The number of events is not sufficient to divide the distribution in several excitation energy intervals [5,7]. Nevertheless, for the ^{5}Li excited states ,T_{app} has been estimated for the two partners of the collision. This "apparent temperature " concept is linked to the populations of excited levels by the expression :

$$\frac{N_1}{N_2} = \frac{(2J_1+1)}{(2J_2+1)} exp\left(-\frac{\Delta\epsilon^*}{Tapp}\right),$$

where N_i are the populations of the levels considered, J_i are their spins and $\Delta\epsilon^*$ is their excitation energy separation. Fig. 6 shows correlation functions obtained in the p+α and d+^{3}He cases giving the populations of $^5\mathrm{Li}_{16.6\ MeV}$ and $^5\mathrm{Li}_{g.s.}$. The apparent temperatures deduced are 5.5±0.5 MeV for the PL source and 5.1±0.5 MeV for the TL source. They are consistent with previous works giving a constant value in this excitation energy domain [13].

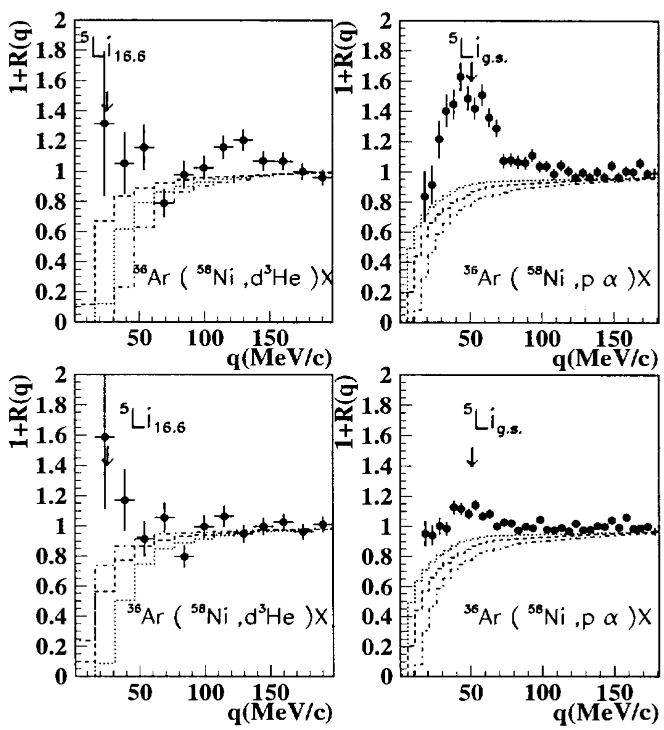

Figure 6: *Correlation functions obtained for vaporization events for the projectile-like (upper part) and the target-like (lower part). The dashed lines represent the background correlation functions.*

As the QSM model can predict the population for each concerned level, it is more direct to compare the experimental populations to the theoretical ones, testing the validity of the proposed assumptions. Since the apparent temperature is in this case about the same for PL and TL, data from PL and TL are mixed to get more statistics. Fig. 7 displays the correlation functions between He and H particles which exhibit visible resonances. The comparison between experimental populations and QSM predictions is shown on Fig.8.

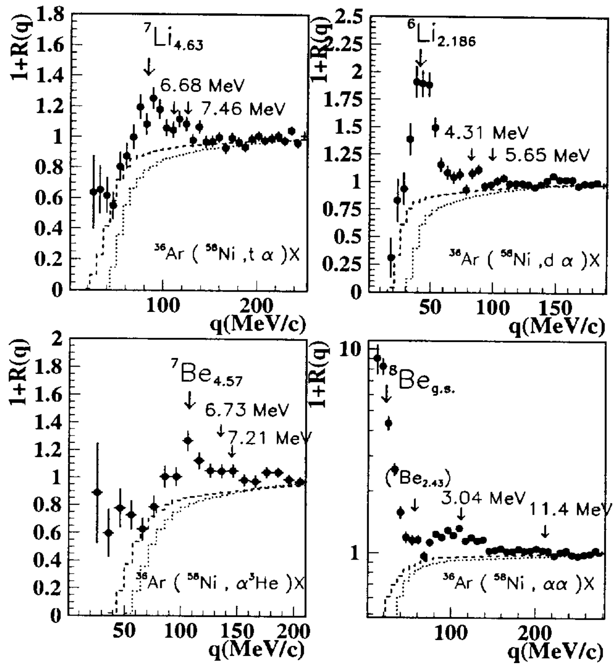

Figure 7: *Correlation functions obtained for vaporization events. The dashed lines represent the background correlation functions.*

Furthermore, the evolution of the populations of unstable fragments with the excitation energy has to be correctly described by the models, particularly between 10 and 20 MeV per nucleon where a phase transition behaviour has been evoked. To get sufficient counting we will consider in the following all PL fragments for the three ϵ^* bins defined in Fig. 2. In Fig. 9 the correlation functions are shown for the three excitation energy bins. Then, the experimental populations are presented together with the predictions of the model for the two assumptions (with or without excluded volumes) (Fig. 10). As for vaporization events, the evolution of the apparent temperature can be compared to the theoretical values (Fig. 11).

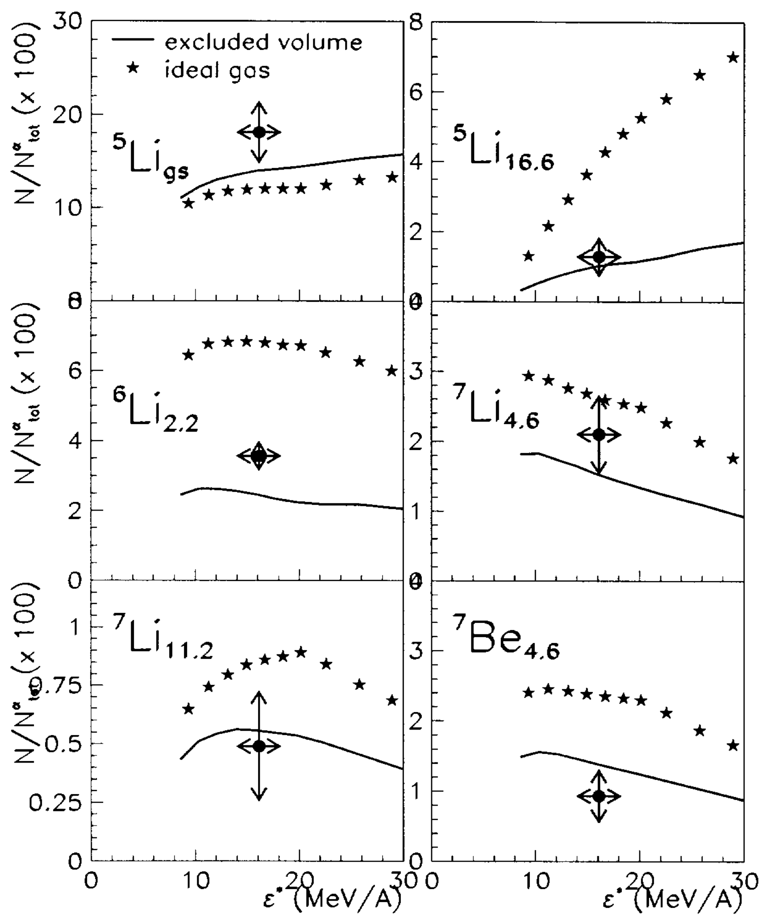

Figure 8: *Comparison of the statistical model results (the line : with excluded volume correction and the stars: the ideal gas) and measured populations for vaporization events (points) .*

Discussion :

The overall analysis leads to the following conclusions :
-for all studied populations the agreement is better with the excluded volume assumption.
-the same behaviour is observed for vaporization events and for binary events of the same excitation energy bin.
-the populations of studied excited states are consistent with a continuous thermodynamical temperature increasing from 10 MeV to 20 MeV.
Even if the description of final state interaction in term of excluded volume is rather rough, experimental results confirm the validity of such an assumption. So, this QSM

model describes with the same set of parameters, the apparent temperature from kinetic energy spectra, isotopic ratio [2,10] and excited states populations.

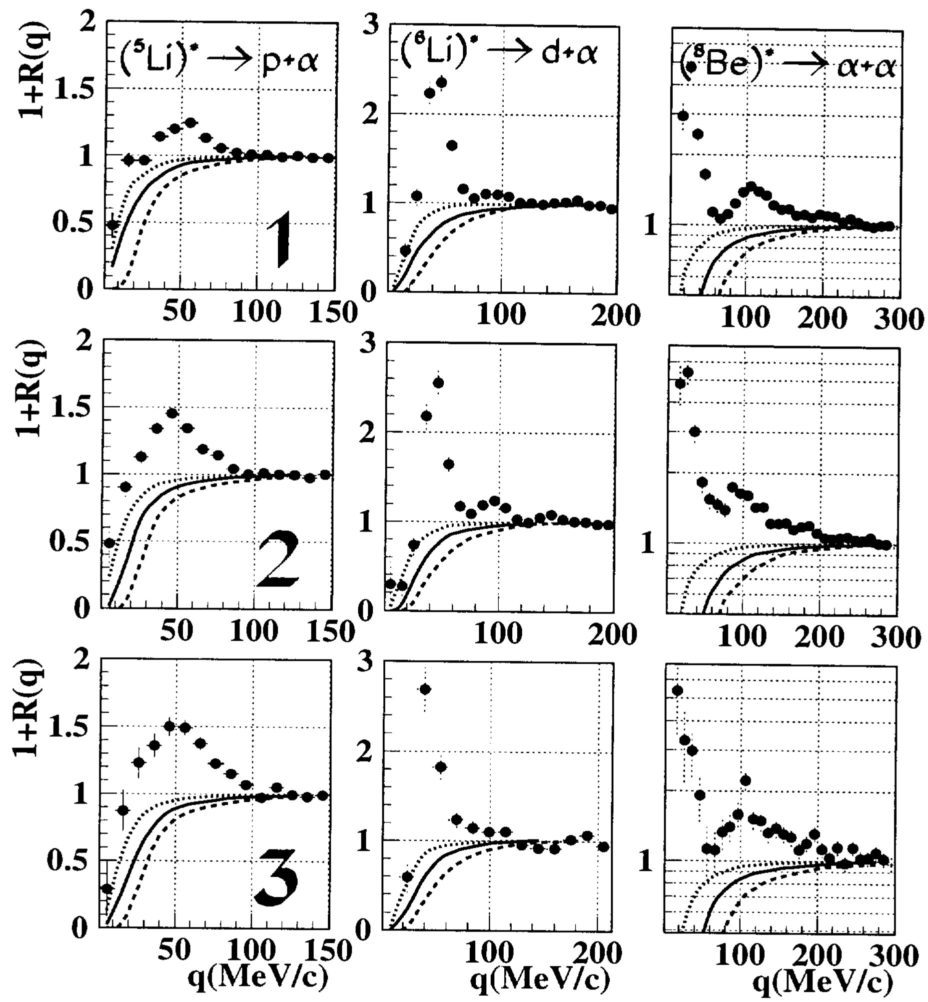

Figure 9: *Proton-Alpha, Deuteron-Alpha and Alpha-Alpha correlation functions for the PL-excitation energy selection (three bins). The dashed lines are extreme bounds for the background correlation functions and the curve represents the mean one.*

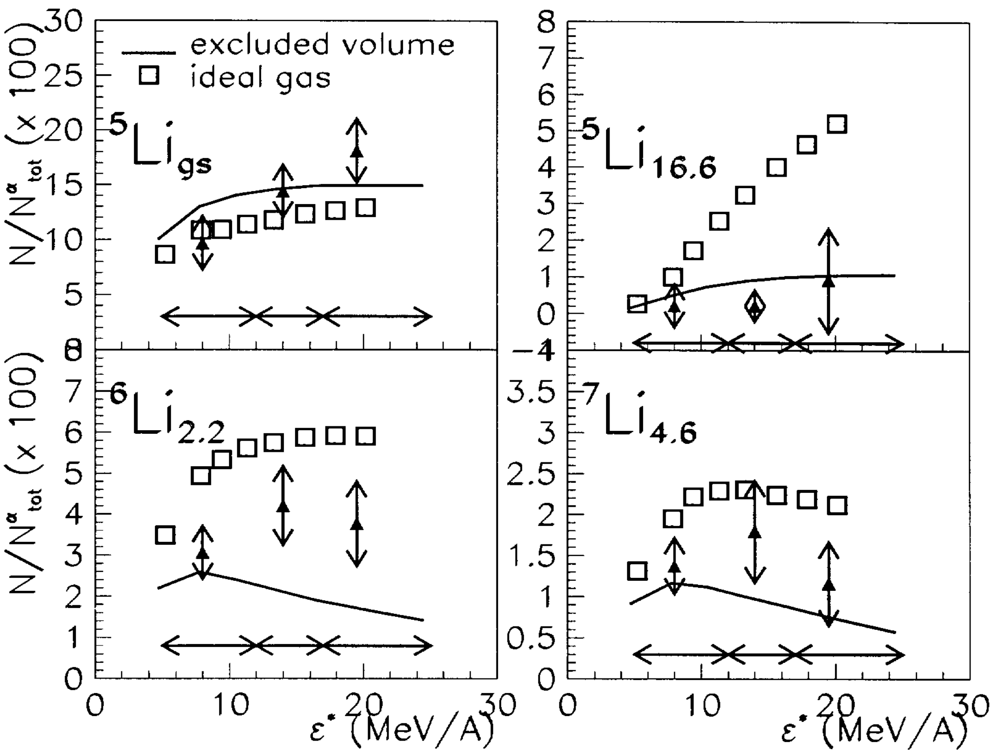

Figure 10: *Populations of four differents excited states as a function of the projectile-like excitation energy (triangles) and comparison with statistical model (open squares and lines).*

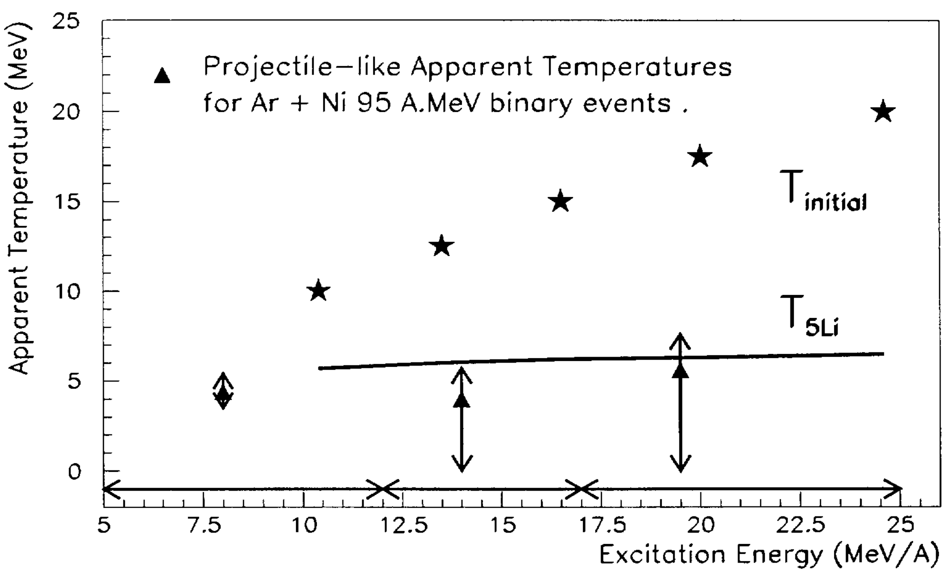

Figure 11: *Apparent temperature estimated with relative populations of ^5Li (triangles) versus the PL excitation energy. The line corresponds to the model prediction with excluded volume and the stars represent the initial temperature.*

References

[1] J. Morrissey, W. Benenson, W. A. Friedman, Annu. Rev. Nucl. Part. Sci. 1994, Vol 44:27-63 and reference therein.

[2] Y.-G. Ma and INDRA Collaboration, Phys. Lett. **390B**, 41(1997).

[3] Kopilov et al, Sov. J. of Nucl. Phys. 18(3) 336(1974).

[4] J. Pouthas et al, Nucl. Inst. and Meth. A357(1995)418.

[5] Ch. O. Bacri and INDRA Collaboration, Phys. Lett. **353B**, 27(1995).

[6] M.F. Rivet and INDRA Collaboration, Phys. Lett.**338B**, 219(1996).

[7] B. Borderie and INDRA Collaboration, Phys. Lett.**338B**, 224(1996).

[8] J. Pochodzalla et al, Phys. Rev. **C35**, 1695(1987).

[9] Y.D. Kim et al, Phys. Rev. **C45**, 338(1992).

[10] F. Gulminelli and D. Durand, pre-print LPCC 96-11 and Nucl. Phys. A, in press.

[11] Z.Chen, C.K. Gelbke, Phys. Rev. **C38** , 2630(1988).

[12] A. Kolomiets et al, Phys. Rev. **C54**, R472(1996).

[13] J.Pochodzalla et al, Proceedind of CRIS'96, ed S. Costa, S. Albergo, A. Insolia, C. Tuve, World Scientific.